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Proceedings of the Combustion Institute 35 (2015) 3591–3599

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# Combustion kinetics and particle fragmentation of raw and torrefied pine shells and olive stones in a drop tube furnace

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Available online 28 June 2014

## Abstract

This study focuses on the combustion kinetics and particle fragmentation of raw and torrefied pine shells and olive stones in a drop tube furnace (DTF). The two biomass fuels studied have been torrefied in a nitrogen inert atmosphere at 280–300 °C. Both raw and torrefied biomass fuels were then burned in the DTF. The data reported includes gas temperature and particle burnout measured along the DTF for five furnace temperatures (900, 950, 1000, 1050 and 1100 °C). In addition, measurements of particulate matter (PM) concentrations and size distributions were made for all the biomass fuels at 1100 °C in the middle and near the exit of the DTF. The results showed that: (1) The high heating value of the torrefied biomass fuels are higher than those of the raw biomass fuels; specifically, for pine shells it increased by 25% and for olive stones by 18%; (2) in contrast with the torrefied olive stones, the torrefied pine shells require similar residence times to attain overall burnout values comparable to those of the untreated material; (3) the kinetic data for both fuels, raw and torrefied, indicates that the torrefaction reduces the activation energy of the present biomass chars; and (4) torrefaction does not promote particle fragmentation even for biomass fuels that present high tendency for it.

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**Keywords:** Drop tube furnace; Pine shells; Olive stones; Torrefaction; Combustion kinetics; Particle fragmentation

## 1. Introduction

Biomass is one of the most favourable alternatives to coal in energy production. In a World driven by the environmental impact of fossil fuels, it is necessary to continuously improve the biomass characteristics in order to overcome drawbacks such as its hydrophilic nature, low heating value,

and high specific energy required in grinding, among others. These drawbacks can be overcome with pre-treatments such as torrefaction. Torrefaction is a thermo-chemical treatment of biomass in an inert atmosphere at temperatures between 250 and 300 °C. During this process the water present in the biomass evaporates and its hemicellulose content reduces yielding a gas consisting of H<sub>2</sub>O, CO, CO<sub>2</sub> and various organic acids. This gas mass flow is typically 20% of the dry input material, while its energy content is only 10%. As compared with the raw biomass, the torrefied

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product has lower H/C and O/C ratios, higher energy density and better grindability and hydrophobic properties [1–7], which makes torrefied biomass an excellent fuel, especially for co-firing in coal-fired power plants.

Studies on the combustion characteristics of torrefied biomass are scarce [e.g., 8–11] and, when reported, have concentrated mostly on qualitative aspects, with very little emphasis on the more fundamental aspects of its combustion behaviour such as combustion kinetics or particle fragmentation. To help redress this problem, the main objective of this study is to examine the combustion kinetics and particle fragmentation of raw and torrefied biomass in a drop tube furnace (DTF). Two biomass fuels were studied, namely pine shells and olive stones, which have been torrefied in a nitrogen inert atmosphere at 280–300 °C. Both the raw and torrefied biomass fuels were then burned in the DTF. The data reported includes gas temperatures and particle burnout measured along the DTF for five furnace temperatures ( $T_w = 900, 950, 1000, 1050$  and  $1100$  °C), which allowed to derivate the kinetic parameters (pre-exponential factor and activation energy) for the devolatilization and char combustion of the raw and torrefied biomass. In addition, measurements of particulate matter (PM) concentrations and size distributions were made for all the biomass fuels at 1100 °C in the middle and at the exit of the DTF in order to evaluate the impact of the torrefaction on particle fragmentation.

## 2. Materials and methods

### 2.1. Drop tube furnace

Figure 1 shows a schematic of the DTF used in this study, which has been described in greater detail elsewhere [12,13]. The combustion chamber of the DTF is an electrically heated ceramic tube with an inner diameter of 38 mm and a length of 1.3 m. The furnace wall temperatures are continuously monitored by eight type-K thermocouples uniformly distributed along the combustion chamber. A water-cooled injector, placed at the top of the DTF, is used to feed the solid fuels and the air to the combustion chamber. A twin screw volumetric feeder transfers the pulverized solid fuels to an ejector system from which the particles are gas-transported to the water-cooled injector.

### 2.2. Experimental methods

Local mean temperature measurements along the combustion chamber axis were obtained using 76  $\mu\text{m}$  diameter fine wire platinum/platinum: 13% rhodium (type-R) thermocouples. The hot

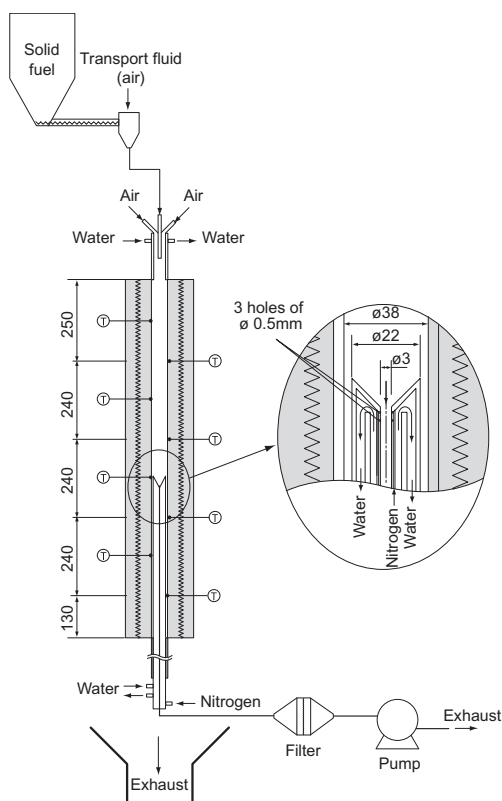


Fig. 1. Schematic of the DTF and auxiliary equipment.

junction was installed and supported on 350  $\mu\text{m}$  wires of the same material located in a twin-bore alumina sheath with an external diameter of 5 mm. The temperature measured with an exposed thermocouple is the gas temperature biased by the furnace wall temperature so that the “true” temperature was estimated based on an energy balance on the thermocouple bead [13]. It was estimated that the measured gas temperature will not exceed the “true” gas temperature by more than 20 °C. This is a type B uncertainty of the GUM (Guide for Uncertainty Measurements) notation.

Particle sampling along the combustion chamber axis was performed with the aid of a 1.5 m long, water-cooled, nitrogen-quenched stainless steel probe [12]. The probe (see Fig. 1) comprised a centrally located 3 mm inner diameter tube, through which quenched samples were evacuated with the aid of a pump. The quenching of the chemical reactions was achieved by direct injection of nitrogen jets through small holes very near to the probe tip. The tube for nitrogen delivery was surrounded by two concentric tubes for probe cooling. On leaving the probe, the solid samples were collected in a Tecora total filter holder equipped with a quartz microfiber filter. Subsequently, the collected solid

samples were placed in an oven at approximately 105 °C to dehydrate. Complete dehydration was ascertained by repeated drying and weighing of the sample until the measured mass became constant. The ash content in the solid samples was finally evaluated following the procedures described in the standard CEN/TS 14775. Particle burnout data were obtained as follows:

$$\psi = \frac{1 - \frac{\omega_f}{\omega_x}}{1 - \omega_f} \quad (1)$$

where  $\psi$  is the particle burnout,  $\omega_f$  is the ash weigh fraction in the input biomass fuel, and  $\omega_x$  is the ash weigh fraction in the char sample.

Uncertainties in char burnout calculations based on the use of ash as a tracer are related to ash volatility at high heating rates and temperatures and ash solubility in water. Our best estimates indicated that the uncertainties in char burnout calculations using ash as a tracer in the present work were negligible [13].

Particulate matter (PM) concentrations and size distributions were made with the aid of a low pressure three-stage cascade impactor (LPI, TCR Tecora). PM was sampled isokinetically from the centreline of the combustion chamber of the DTF using the water-cooled, nitrogen-quenched stainless steel probe referred to above. The LPI used allowed collecting three particulate cut sizes during the same sampling: PM with diameters above 10  $\mu\text{m}$  (PM10), PM with diameters between 2.5 and 10  $\mu\text{m}$ , and PM with diameters below 2.5  $\mu\text{m}$  (PM2.5). In order to avoid condensation along the line connecting the probe outlet to the impactor inlet and also inside the impactor, a heating jacket (model Winkler WOTX1187) was used during sampling. PM was collected on quartz microfiber filters, which were dried in an oven and weighted before each test. After each test, the filters were again dried, to eliminate moisture, and weighted to determine the quantity of PM captured.

### 2.3. Test conditions

The solid fuels studied in this work included raw and torrefied pine shells and olive stones. Both raw biomass fuels were sieved to 1 mm size and the particle size distribution measured using the Malvern 2600 Particle Size Analyzer. The biomass fuels were torrefied in an insulated stainless steel container through which 3 L/min of nitrogen at 310 °C was passed during 1 h. During the process the biomass temperature varied between 280 and 300 °C. Table 1 shows the properties of the raw and torrefied biomass fuels, including the fuel ashes composition. The table includes the properties of a United Kingdom bituminous coal for comparison purposes. Note that the particle size distribution of the torrefied biomass fuels were

similar to those of the raw biomass fuels as indicated by the measurements performed with the aid of the Malvern Analyser. Moreover, particle shapes of the raw and torrefied biomass fuels have been examined with the aid of a scanning electron microscope and no significant differences between them were noticed.

In this study, measurements were carried out for all biomass fuels for DTF wall temperatures of  $T_w = 900, 950, 1000, 1050$  and 1100 °C, and inlet air at room temperature. The solid fuels feed rate was around 23 g/h and the total air flow rate was 4 L/min. The initial particle velocity was estimated, from the inlet air flow at room temperature, to be  $\sim 0.3$  m/s.

## 3. Results and discussion

### 3.1. Raw versus torrefied biomass fuels

Table 1 shows the properties of the raw and torrefied biomass fuels. As expected, torrefaction significantly reduced the moisture content of the biomass fuels; specifically, from 13.9 to 1 wt% for the pine shells, and from 9.4 to 0.3 wt% for the olive stones. Table 1 also reveals that the high heating value (HHV) increased significantly with torrefaction; specifically, from 18.82 to 23.52 MJ/kg for the pine shells, and from 17.54 to 20.67 MJ/kg for the olive stones. Figure 2 shows the van Krevelen diagram of the biomass fuels and bituminous coal. It is clear that the H/C atomic ratio correlates well with the O/C atomic ratio (correlation coefficient of  $R^2 = 0.9476$ ) and that the torrefaction decreases both the oxygen and hydrogen contents of the raw biomass fuels approaching them towards those of coal.

### 3.2. Gas temperature and particle burnout

Figure 3 shows the temperature profiles along the axis of the DTF for all solid fuels and reactor wall temperatures studied. In the near burner region the raw biomass fuels present slightly higher temperatures than the torrefied biomass fuels because of the more intense devolatilization and combustion rates associated to the raw materials. As the axial distance from the burner ( $x$ ) increases the differences between the measured temperatures diminish.

Figure 4 shows the particle burnout profiles along the axis of the DTF for all solid fuels and reactor wall temperatures studied. Note that due to the high volatile matter content of the raw and torrefied biomass fuels most of the data refer to the devolatilization process. Consistently with the measured temperatures (Fig. 3), Fig. 4 reveals that the particle burnout values in the near burner region are higher for the raw biomass fuels than

Table 1  
Properties of the raw and torrefied biomass fuels. Coal is included for comparison purposes.

| Parameter                                    | Pine shells |           | Olive stones |           | Coal  |
|----------------------------------------------|-------------|-----------|--------------|-----------|-------|
|                                              | Raw         | Torrefied | Raw          | Torrefied |       |
| <i>Proximate analysis (wt%, as received)</i> |             |           |              |           |       |
| Volatiles                                    | 58.9        | 69.4      | 57.8         | 60.6      | 44.6  |
| Fixed Carbon                                 | 25.9        | 27.6      | 19.7         | 23.1      | 51.4  |
| Moisture                                     | 13.9        | 1.0       | 9.4          | 0.3       | 1.7   |
| Ash                                          | 1.3         | 2.0       | 13.1         | 16.0      | 2.3   |
| <i>Ultimate analysis (wt%, daf)</i>          |             |           |              |           |       |
| Carbon                                       | 47.8        | 54.4      | 43.2         | 47.8      | 79.3  |
| Hydrogen                                     | 5.6         | 5.5       | 5.6          | 5.1       | 5.9   |
| Nitrogen                                     | 0.3         | 0.4       | 1.9          | 2.3       | 1.9   |
| Sulphur                                      | 0.0         | 0.0       | 0.0          | 0.0       | 0.5   |
| Oxygen                                       | 46.3        | 39.7      | 49.3         | 44.8      | 12.4  |
| High heating value (MJ/kg)                   | 18.82       | 23.52     | 17.54        | 20.67     | 35.04 |
| <i>Ash analysis (wt%, dry basis)</i>         |             |           |              |           |       |
| SiO <sub>2</sub>                             | 9.6         |           | 30.4         |           | 39.4  |
| Al <sub>2</sub> O <sub>3</sub>               | 11.9        |           | 10.6         |           | 23.2  |
| Fe <sub>2</sub> O <sub>3</sub>               | 2.1         |           | 9.9          |           | 24.7  |
| CaO                                          | 50.9        |           | 9.9          |           | 3.5   |
| SO <sub>3</sub>                              | 2.0         |           | 0.7          |           | 1.5   |
| MgO                                          | 12.1        |           | 7.2          |           | 1.0   |
| TiO <sub>2</sub>                             | 0.0         |           | 0.9          |           | 1.7   |
| P <sub>2</sub> O <sub>5</sub>                | 5.6         |           | 7.4          |           | 0.2   |
| K <sub>2</sub> O                             | 4.1         |           | 18.7         |           | 1.2   |
| Na <sub>2</sub> O                            | 0.8         |           | 2.9          |           | 2.6   |
| Other oxides                                 | 0.9         |           | 1.4          |           | 1.0   |
| <i>Particle size (μm)</i>                    |             |           |              |           |       |
| Under 30                                     | 13.6        |           | 9.9          |           | 38.4  |
| Under 70                                     | 28.5        |           | 17.5         |           | 61.4  |
| Under 100                                    | 34.7        |           | 21.3         |           | 69.9  |
| Under 300                                    | 53.1        |           | 37.1         |           | 94.2  |
| Under 500                                    | 67.0        |           | 49.8         |           | 100   |
| Under 1000                                   | 95.1        |           | 94.1         |           | 100   |
| Under 2000                                   | 100         |           | 100          |           | 100   |

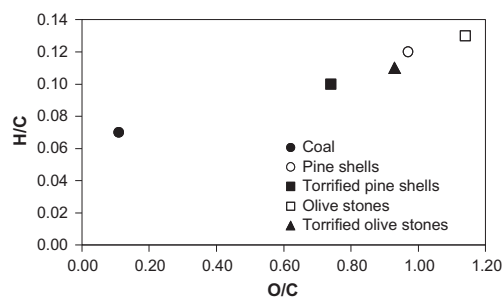


Fig. 2. Van Krevelen diagram of the biomass fuels and coal.

for the torrefied biomass fuels, with the differences diminishing as  $x$  augments.

Figure 4 also shows that the raw pine shells present the higher particle burnout values regardless of the reactor wall temperature. Specifically, at  $x = 200$  mm the raw pine shells burnout varies

from ~63% at 900 °C to ~79% at 1100 °C, and at  $x = 1100$  mm it varies from ~95% at 900 °C to ~99% at 1100 °C. The corresponding values for the torrefied pine shells are ~37% and ~69% at  $x = 200$  mm, and ~85% and ~99% at  $x = 1100$  mm. These results indicate that, despite the lower initial burnout rates, the torrefied pine shells do not require longer residence times to attain overall burnout values comparable to those of the untreated material.

Both the raw and torrefied olive stones present particle burnout values significantly lower than those of the raw and torrefied pine shells, respectively. Figure 4 indicates that at  $x = 200$  mm the raw material burnout varies from ~5% at 900 °C to ~27% at 1100 °C, and at  $x = 1100$  mm it varies from ~69% at 900 °C to ~94% at 1100 °C. The corresponding values for the torrefied olive stones are ~1% and ~15% at  $x = 200$  mm, and ~63% and ~86% at  $x = 1100$  mm. In this case, therefore, the torrefied olive stones require longer residence times to attain overall burnout values comparable to those of the raw material.

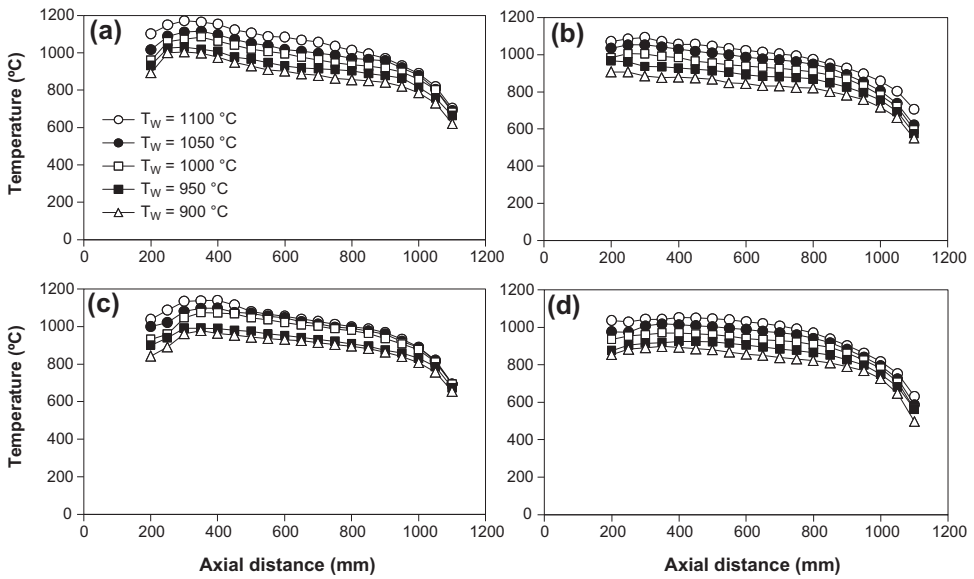


Fig. 3. Temperature profiles along the axis of the DTF (a) pine shells, (b) torrifed pine shells, (c) olive stones, and (d) torrifed olive stones.

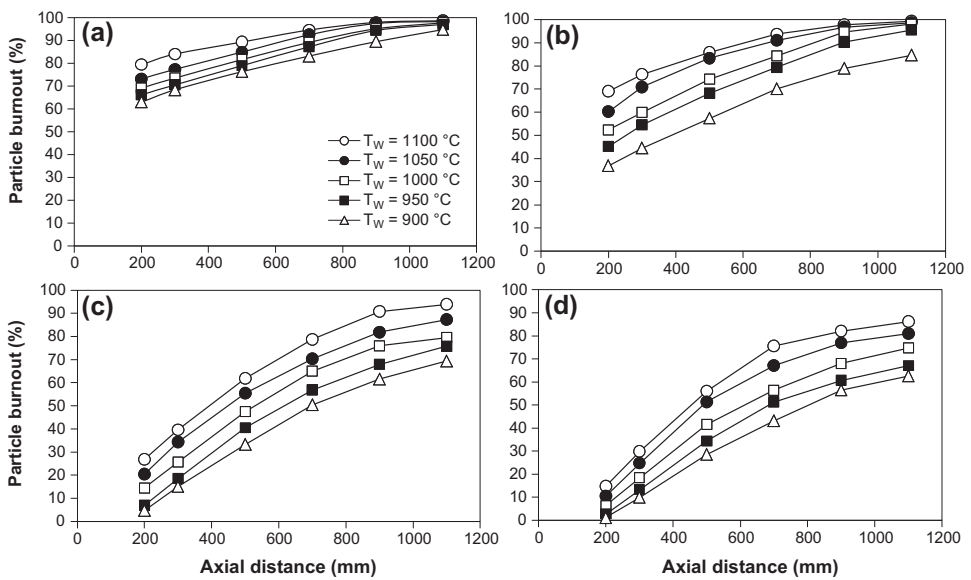


Fig. 4. Particle burnout profiles along the axis of the DTF (a) Pine shells, (b) torrifed pine shells, (c) olive stones, and (d) torrifed olive stones.

### 3.3. Combustion kinetics

The adopted model for the particle devolatilization was the single first order model expressed as [14]:

$$\frac{dv}{dt} = K_v(1 - \psi) \quad (2)$$

where

$$K_v = A_v e^{-\frac{E_v}{RT}} \quad (3)$$

Equation (2) can be written as follows:

$$\text{Ln} \left( \frac{\frac{dv}{dt}}{1 - \psi} \right) = -\frac{E_v}{RT} + \text{Ln} (A_v) \quad (4)$$

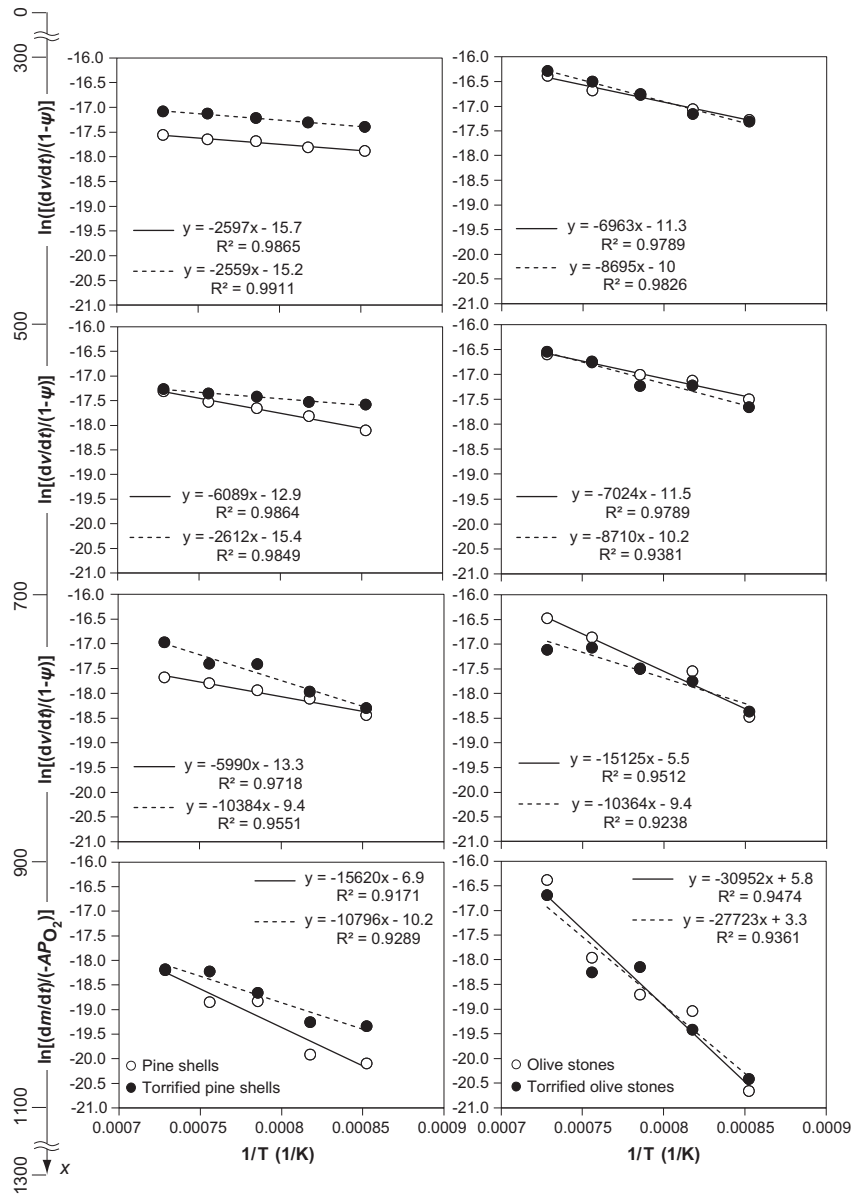


Fig. 5. Linear regression to evaluate the kinetic parameters along the DTF (a)  $300 < x < 500$  mm, (b)  $500 < x < 700$  mm, (c)  $700 < x < 900$  mm, and (d)  $900 < x < 1100$  mm.

where  $\frac{dm}{dt}$  stands for the volatile release with time,  $\psi$  is the particle burnout, and  $E_v$  and  $A_v$  represent the activation energy and the pre-exponential factor for the devolatilization, respectively.

Similarly, for the char combustion [13]:

$$\frac{dm}{dt} = -AK_c P_{O_2} \quad (5)$$

where

$$K_c = A_c e^{\frac{E_c}{RT}} \quad (6)$$

Equation (5) can be written as follows:

$$\ln \left( \frac{\frac{dm}{dt}}{-AP_{O_2}} \right) = -\frac{E_c}{RT} + \ln(A_c) \quad (7)$$

where  $\frac{dm}{dt}$  is the mass loss of the particle with time,  $A$  is the particle area,  $P_{O_2}$  is the partial pressure of the oxidant,  $E_c$  is the activation energy for the char combustion of a given fuel,  $R$  is the universal gas constant,  $T$  is the particle temperature and  $A_c$  is the pre-exponential factor for the char combustion.

Table 2  
Properties of the raw and torrefied biomass fuels.

| DTF section         | Pine shells        |                 |           |                    | Olive stones       |                 |           |                 |
|---------------------|--------------------|-----------------|-----------|--------------------|--------------------|-----------------|-----------|-----------------|
|                     | Raw                |                 | Torrefied |                    | Raw                |                 | Torrefied |                 |
|                     | $E_{v/c}$ (kJ/mol) | $A_{v/c}$ (1/s) | $R^2$     | $E_{v/c}$ (kJ/mol) | $E_{v/c}$ (kJ/mol) | $A_{v/c}$ (1/s) | $R^2$     | $A_{v/c}$ (1/s) |
| $300 < x < 500$ mm  | $21.6 \pm 0.3$     | 0.3             | 0.9865    | $21.3 \pm 0.3$     | $57.9 \pm 0.8$     | 19.1            | 0.9789    | $72.3 \pm 1.0$  |
| $500 < x < 700$ mm  | $50.6 \pm 0.7$     | 4.1             | 0.9864    | $21.7 \pm 0.3$     | $58.4 \pm 0.8$     | 16.9            | 0.9789    | $72.4 \pm 1.0$  |
| $700 < x < 900$ mm  | $49.8 \pm 0.7$     | 2.8             | 0.9718    | $86.3 \pm 1.2$     | $125.8 \pm 1.8$    | $6.9E + 03$     | 0.9512    | 58.9            |
| $900 < x < 1100$ mm | $129.9 \pm 1.9$    | 1670.4          | 0.9171    | $89.8 \pm 1.3$     | $254.8 \pm 3.7$    | $5.5E + 08$     | 0.9474    | $134.4$         |
|                     |                    |                 |           |                    |                    |                 |           | $4.2E + 07$     |
|                     |                    |                 |           |                    |                    |                 |           | 0.9361          |

Figure 5 shows the linear regression to evaluate the kinetic parameters along the DTF. The data points plotted in the various panels of Fig. 5 were calculated by applying either Eq. (4) or (7) between two consecutive measured (particle burnout)  $x$ -positions in the DTF. Table 2 lists the activation energies and the pre-exponential factors for four sections of the reactor, namely for  $300 < x < 500$  mm,  $500 < x < 700$  mm,  $700 < x < 900$  mm, and  $900 < x < 1100$  mm. In regard to the raw pine shells, the present activation energy data suggest that there are three different stages: a first devolatilization stage in the region  $300 < x < 500$  mm, a second devolatilization stage in the region  $500 < x < 900$  mm, and a third char combustion stage in the region  $900 < x < 1100$  mm (cf. Fig. 4). The torrefied pine shells, however, presents only two stages, namely a devolatilization stage in the region  $300 < x < 700$  mm and a char combustion stage in the region  $700 < x < 1100$  mm. This may be attributed to the loss of the volatile matter during the torrefaction process, which reduced the extension of the devolatilization process and augmented the duration of the char combustion process.

The activation energy data for the raw and torrefied olive stones indicate a similar behaviour with three different stages for both fuels: a first devolatilization stage in the region  $300 < x < 700$  mm, a second devolatilization plus char combustion stage in the region  $700 < x < 900$  mm, and a third char combustion stage in the region  $900 < x < 1100$  mm (cf. Fig. 4).

The present kinetic data for both fuels, raw and torrefied, indicates that torrefaction reduces the activation energy of the studied biomass chars. Di Blasi [15] made a compilation of kinetic data for a range of biomass chars and found values for the activation energy between 144 and 230 kJ/mol, which are in line with the ones found in this study. The uncertainties in the activation energy are mainly associated with those from the temperature and burnout measurements. In the present study these led to uncertainties in the activation energy below 2% (see Table 2).

### 3.4. Particle fragmentation

Figure 6 shows the size-classified PM concentrations at  $x = 500$  mm and at  $x = 1100$  mm for a reactor wall temperature of  $T_w = 1100$  °C for the four biomass fuels studied. In the case of the raw pine shells (Fig. 6a) the particle burnout increases from 89.4% to 98.7% between  $x = 500$  and 1100 mm, while the PM below 10  $\mu$ m (PM2.5 plus PM2.5–PM10) increases from 15% to 39%; in the case of the torrefied pine shells (Fig. 6b) the burnout increases from 85.8% to 99.4% between  $x = 500$  and 1100 mm, while the PM below 10  $\mu$ m increases from 16% to 42.5%. This suggests that it exists particle fragmentation between  $x = 500$  and 1100 mm

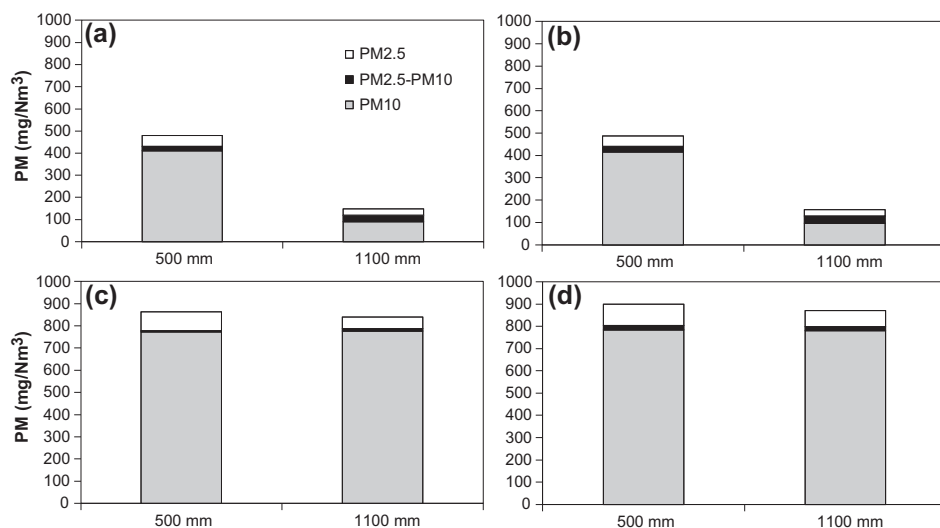


Fig. 6. Size-classified PM concentrations at  $x = 500$  mm and at  $x = 1100$  mm for a wall temperature  $T_w = 1100$  °C (a) pine shells, (b) torrified pine shells, (c) olive stones, and (d) torrified olive stones.

for both biomass fuels (raw and torrified), but that particle fragmentation was not promoted by the torrefaction process.

In the case of the raw olive stones (Fig. 6c) the particle burnout increases from 61.8% to 93.8% between  $x = 500$  and 1100 mm, while the PM below 10  $\mu\text{m}$  decreased from 10.5% to 7.1%; in the case of the torrified olive stones (Fig. 6d) the burnout increases from 55.9% to 86.1% between  $x = 500$  and 1100 mm, while the PM below 10  $\mu\text{m}$  decreases from 12.5% to 10.3%. Against this background it can be concluded with reasonable justification that again particle fragmentation was not promoted by the torrefaction process, although in this case the particle fragmentation between  $x = 500$  and 1100 mm for both biomass fuels appears also do not occur.

#### 4. Conclusions

The major conclusions from this work can be summarized as follows:

1. The high heating value of the torrified biomass fuels are higher than those of the raw biomass fuels; specifically, for pine shells it increased by 25% and for olive stones by 18%.
2. Both the raw and torrified olive stones present particle burnout values significantly lower than those of the raw and torrified pine shells. In contrast with the torrified olive stones, the torrified pine shells require similar residence times to attain overall burnout values comparable to those of the untreated material.

3. The kinetic data for both fuels, raw and torrified, indicates that the torrefaction reduces the activation energy of the present biomass chars.
4. PM concentrations and size distributions made for all biomass fuels at 1100 °C in the middle and near the exit of the DTF indicated that torrefaction does not promote particle fragmentation even for biomass fuels that present high tendency for it.

#### Acknowledgement

This work was supported by Fundação para a Ciência e a Tecnologia (FCT), through IDMEC, under LAETA Pest-OE/EME/LA0022.

#### References

- [1] J.J. Chew, V. Doshi, *Renew. Sust. Energy Rev.* 15 (2011) 4212–4222.
- [2] K. Svoboda, M. Porohely, M. Hartman, J. Martinec, *Fuel Process. Technol.* 90 (2009) 629–635.
- [3] W.-H. Chen, W.-Y. Cheng, K.-M. Lu, Y.-P. Huang, *Appl. Energy* 88 (2011) 3636–3644.
- [4] V. Repellin, A. Govin, M. Rolland, R. Guyonnet, *Biomass Bioenerg.* 34 (2010) 923–930.
- [5] M. Phanphanich, S. Mani, *Bioresour. Technol.* 102 (2010) 1246–1253.
- [6] M.J. Prins, K.J. Ptasiński, F. Janssen, *J. Anal. Appl. Pyrol.* 77 (2006) 35–40.
- [7] B. Moghtaderi, C. Meesri, T.F. Wall, *Fuel* 83 (2004) 745–750.
- [8] T.G. Bridgeman, J.M. Jones, I. Shield, P.T. Williams, *Fuel* 87 (2008) 844–856.

- [9] W.-H. Chen, P.-C. Kuo, *Energy* 36 (2011) 803–811.
- [10] M. Broström, A. Nordin, L. Pommer, C. Branca, C. Di Blasi, *J. Anal. Appl. Pyrol.* 96 (2012) 100–109.
- [11] M.J.C. van der Stelt, H. Gerhauser, J.H.A. Kiel, K.J. Ptasinski, *Biomass Bioenerg.* 35 (2011) 3748–3762.
- [12] G. Wang, R. Zander, M. Costa, *Fuel* 115 (2014) 452–460.
- [13] G. Wang, R.B. Silva, J.L.T. Azevedo, S. Martins-Dias, M. Costa, *Fuel* 117 (2014) 809–824.
- [14] A. Williams, J.M. Jones, L. Ma, M. Pourkashanian, *Prog. Energy Combust. Sci.* 38 (2012) 113–137.
- [15] C. Di Blasi, *Prog. Energy Combust. Sci.* 35 (2009) 121–140.